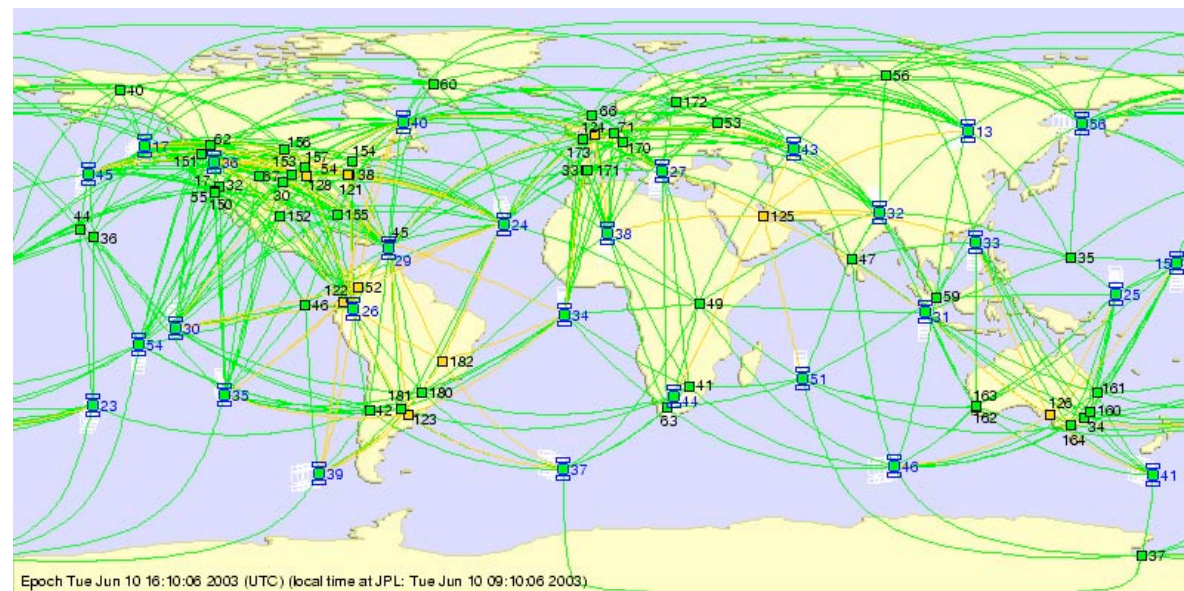
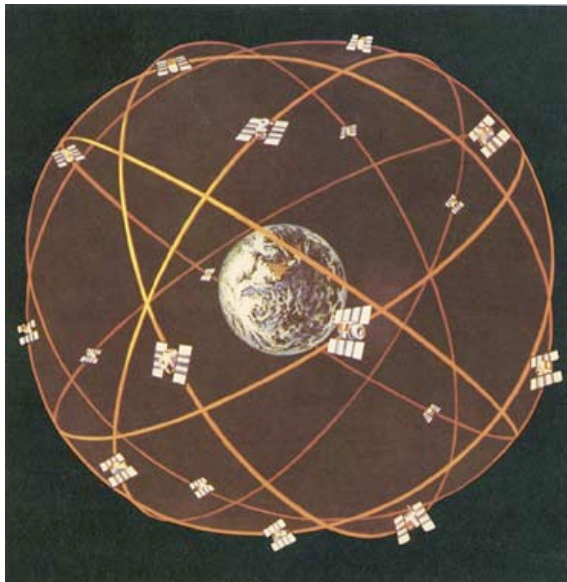


GPS Performance Monitoring With the NASA Global Differential GPS System

Yoaz Bar-Sever and Michael Armatys

Jet Propulsion Laboratory





NASA's Global Differential GPS System



Terrestrial and
airborne users

Land lines
Iridium
Inmarsat

GDGPS Operations Center



Uplink

TDRS



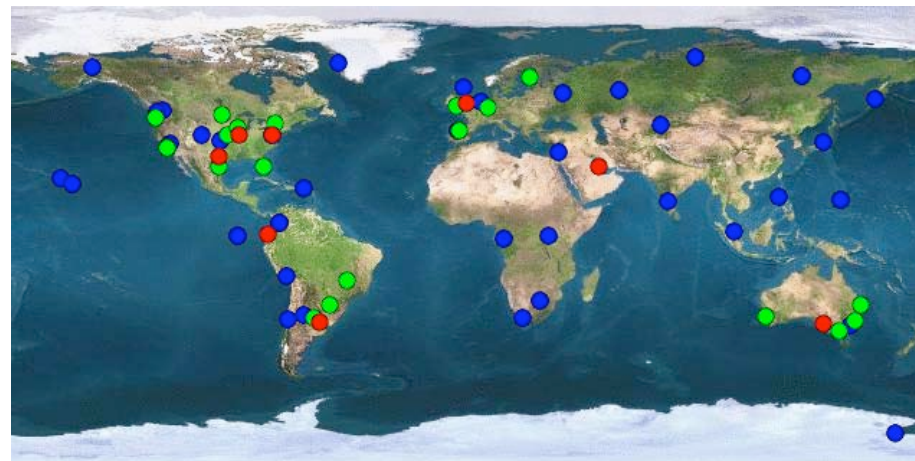
Broadcast



Space users

Frame
Internet

NASA's global real time network



Developed under the
NASA Advanced
Information Systems
Technology Program

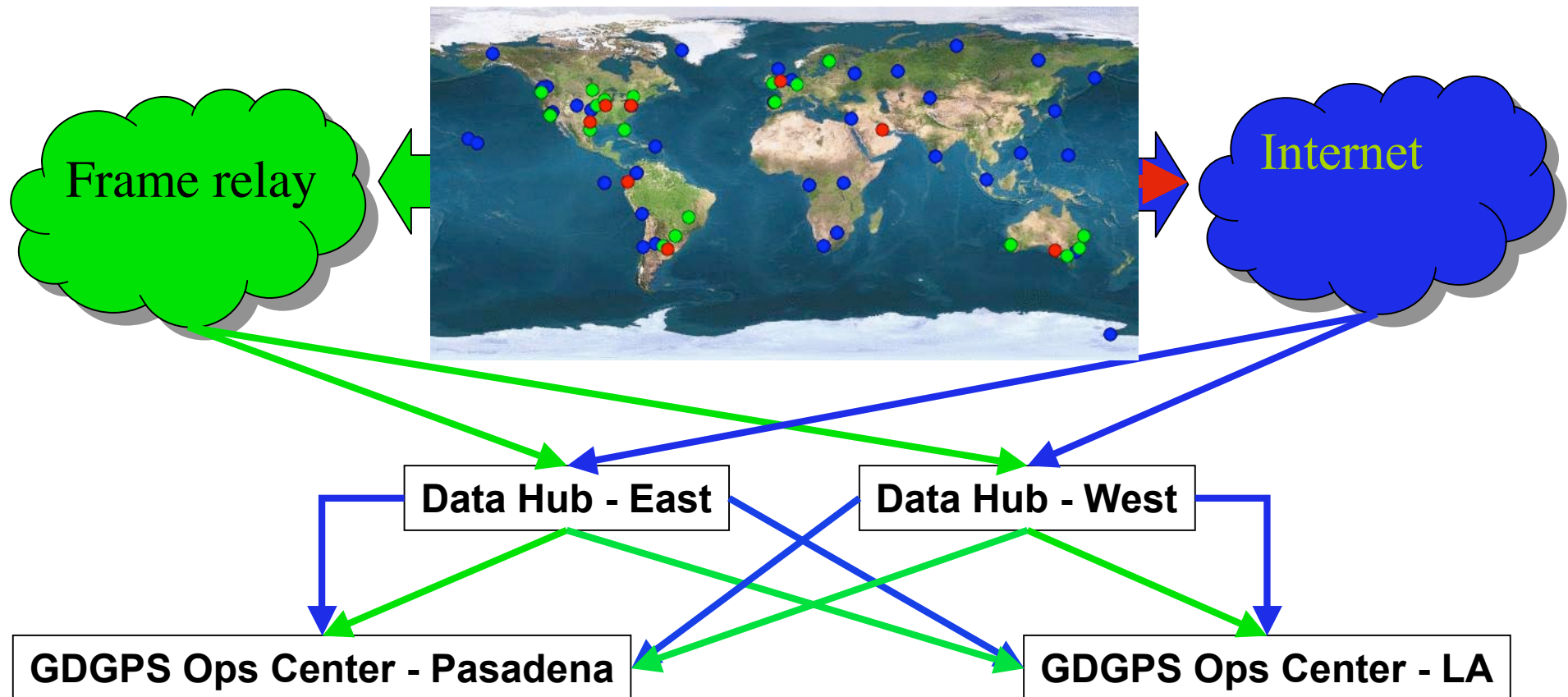
For more information see:
<http://gipsy.jpl.nasa.gov/igdg>



Robust Network Architecture



- Reliability through redundancy: **No single points of failure**
- Architecture integrates **dedicated comm lines** with multiple **internet channels**
- Automatic fault detection and data rerouting ensures redundancy even during failures
- USNO Master Clock provides system reference time through two sites

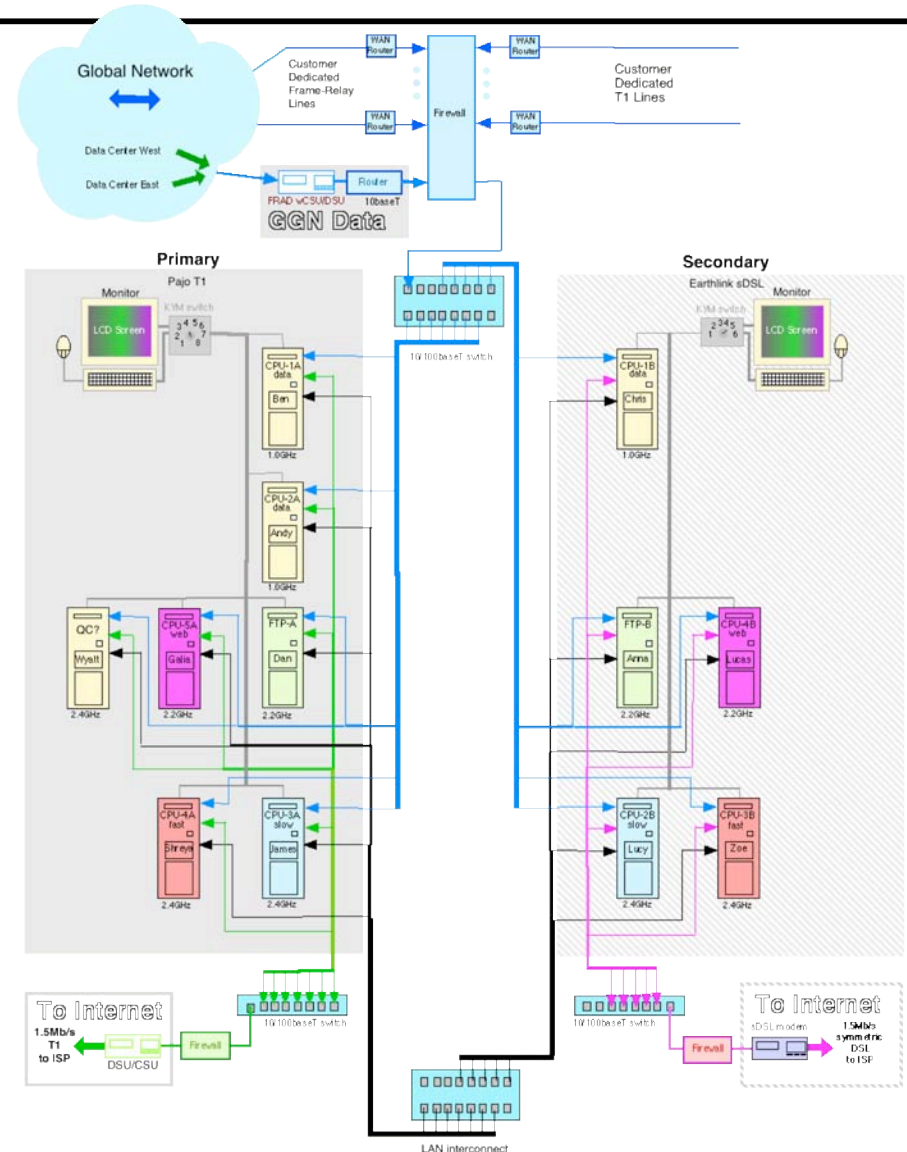




Mature and Reliable Ground Operations



- Triple redundancy for high reliability even during system maintenance
- Multiple user access channels
 - Secure leased lines
 - VPN
 - Open internet
 - Modems
- Global reach
 - Iridium
 - Inmarsat
 - TDRSS (for space applications)
- Continuous Web monitoring in the public domain
- **99.99% reliability since 2000**



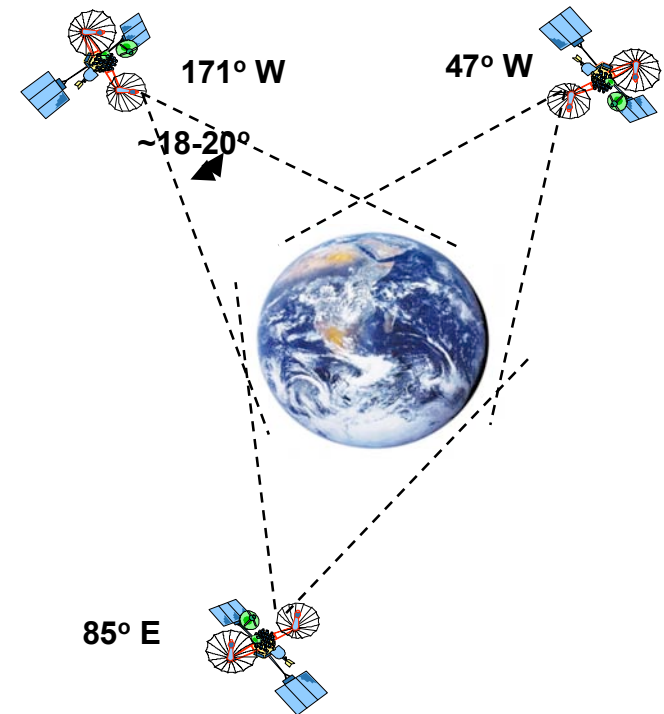


Gold Standard for Accuracy and Reliability



The NASA GDGPS system is widely recognized for its superior accuracy and operational reliability

- Major corporations base their global operations on the GDGPS service
- New NASA service for satellite navigation with TDRSS in 2003



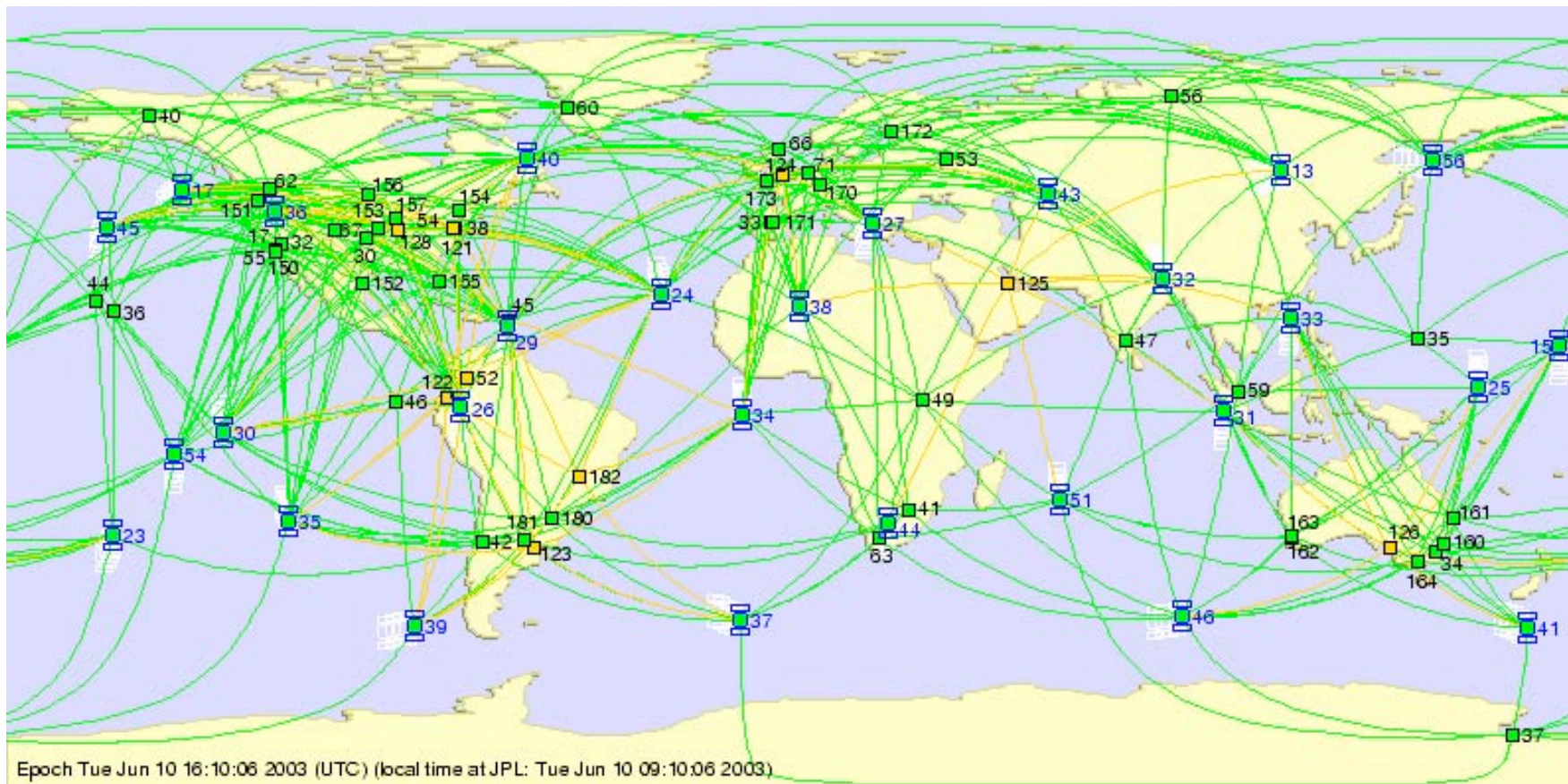


Uniquely Powerful GPS Monitoring



The GDGPS System tracks each GPS satellite by at least **5 sites**, and by **15 sites** on average, enabling robust, real-time GPS performance monitoring with **4 sec** to alarm

The GDGPS GPS Integrity Monitor





GPS Integrity Monitoring with the NASA GDGPS System



GDGPS is ideally suited for GPS integrity/performance monitoring:

- State space approach (as in the OCS) enables separation of orbit and clock errors
- **Large global network allows estimation of clocks independent of models (unlike OCS), enabling prediction of integrity failures**
- **Large global network enables implementation of majority voting schemes**
- High operational reliability
- **High performance monitoring: high accuracy, multiple metrics, absolute metrics**
- **Independent of any other system employed in support of GPS operations**

GDGPS has a fundamental built-in integrity monitoring capability:

Integrity ~ precise orbit/clocks - broadcast orbits/clocks

Leverage the Government's (mainly NASA) tens of million dollar investment in the GDGPS infrastructure

The potential was first recognized by the Aerospace Corporation



GDGPS Integrity Monitoring Demonstration



Concept: Develop a parallel process within the GDGPS system that is optimized for integrity monitoring

- Monitor all satellites healthy and unhealthy
- Implement web-based user interface
- Enable majority voting schemes and other integrity 'rules'
- Implement data authentication to swart spoofing
- Implement 4 sec alarms
- Adapt to evolving user needs and changing constellation

A prototype integrity monitor was developed in close collaboration with the Aerospace Corporation.

The prototype was implemented as a secure web site, with access limited to authorized personnel (mainly 2SOPS and support contractors)

- Served from a single computer at the Pasadena Operations Center
- Access is via the internet; limited capacity
- Unattended operation



Demo of the GDGPS Integrity Monitoring Prototype



GPS Integrity Monitor: Table sorted by SVN
without auto-update ([Go to version with 30-sec auto-update](#))

SVN	PRN	Orbit	Block	Performance metrics			Orbit/Clock error metrics				Link Statistics					SVN
				URE	URA	URE/URA	UREE	CLK	RSS	RAC	Total	Good	Bad	Missing	AOD	
(2)	(2)	(2)	(2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(plot,2)	(2)
13	2	B-5	II	0.74	4.00	0.18	0.46	-1.16	1.07	plot	33	33	0	0	17.0	13
15	15	D-5	II	0.31	2.00	0.15	1.18	-0.94	1.97	plot	16	15	0	1	0.5	15
17	17	D-6	II	-	-	-	-	-	-	plot	-	-	-	-	-	17
23	23	E-5	IIA	2.38	2.00	1.19	0.81	2.27	5.85	plot	7	7	0	0	0.1	23
24	24	D-1	IIA	0.27	2.00	0.13	1.47	1.24	1.82	plot	16	16	0	0	6.6	24
25	25	A-2	IIA	1.21	2.00	0.61	0.55	0.67	1.04	plot	23	23	0	0	2.3	25
26	26	F-2	IIA	0.91	2.00	0.45	0.53	-0.39	1.22	plot	11	11	0	0	1.9	26
27	27	A-4	IIA	2.28	2.00	1.14	0.47	-1.90	2.22	plot	21	21	0	0	14.6	27
29	29	F-5	IIA	1.66	2.00	0.83	0.38	-1.30	0.94	plot	12	12	0	0	2.1	29
30	30	B-2	IIA	0.75	2.00	0.37	0.18	-0.89	0.73	plot	12	12	0	0	4.6	30
31	31	C-3	IIA	0.92	2.00	0.46	0.30	0.91	2.16	plot	25	25	0	0	14.2	31
32	1	F-4	IIA	1.46	4.00	0.36	1.29	0.23	6.87	plot	32	32	0	0	17.6	32
33	3	C-2	IIA	1.26	2.83	0.45	0.72	-1.93	1.73	plot	32	32	0	0	10.2	33
34	4	D-4	IIA	0.91	2.00	0.45	0.88	1.54	3.36	plot	11	11	0	0	8.2	34
35	5	B-4	IIA	0.42	2.00	0.21	0.11	0.48	0.61	plot	10	10	0	0	6.1	35
36	6	C-1	IIA	2.77	2.00	1.38	2.10	4.69	5.11	plot	13	13	0	0	2.9	36
37	7	C-4	IIA	0.41	2.00	0.20	0.30	0.48	1.85	plot	9	9	0	0	10.3	37
38	8	A-3	IIA	2.91	2.83	1.03	0.12	-2.85	0.80	plot	17	17	0	0	13.7	38
39	9	A-1	IIA	0.64	2.00	0.32	0.52	-0.43	3.70	plot	12	12	0	0	7.1	39
40	10	E-3	IIA	1.63	2.00	0.82	0.69	-0.97	1.91	plot	14	13	1	0	4.6	40
41	14	F-1	IIR	0.60	2.83	0.21	0.87	-1.12	3.43	plot	8	8	0	0	23.2	41
43	13	F-3	IIR	0.36	2.00	0.18	0.23	-0.17	1.25	plot	29	28	0	1	16.2	43
44	28	B-3	IIR	0.34	2.83	0.12	0.14	0.31	1.00	plot	9	9	0	0	12.8	44
45	21	D-3	IIR	2.03	2.00	1.01	0.60	1.86	4.28	plot	14	13	0	1	2.9	45
46	11	D-2	IIR	0.74	2.83	0.26	0.10	-0.74	0.70	plot	7	7	0	0	19.1	46
51	20	E-1	IIR	0.37	2.83	0.13	0.44	0.09	1.95	plot	24	24	0	0	17.9	51
54	18	E-4	IIR	0.22	2.00	0.11	0.35	-0.39	1.45	plot	6	6	0	0	1.4	54
56	16	B-1	IIR	0.59	2.00	0.29	0.24	0.40	1.28	plot	30	30	0	0	0.7	56



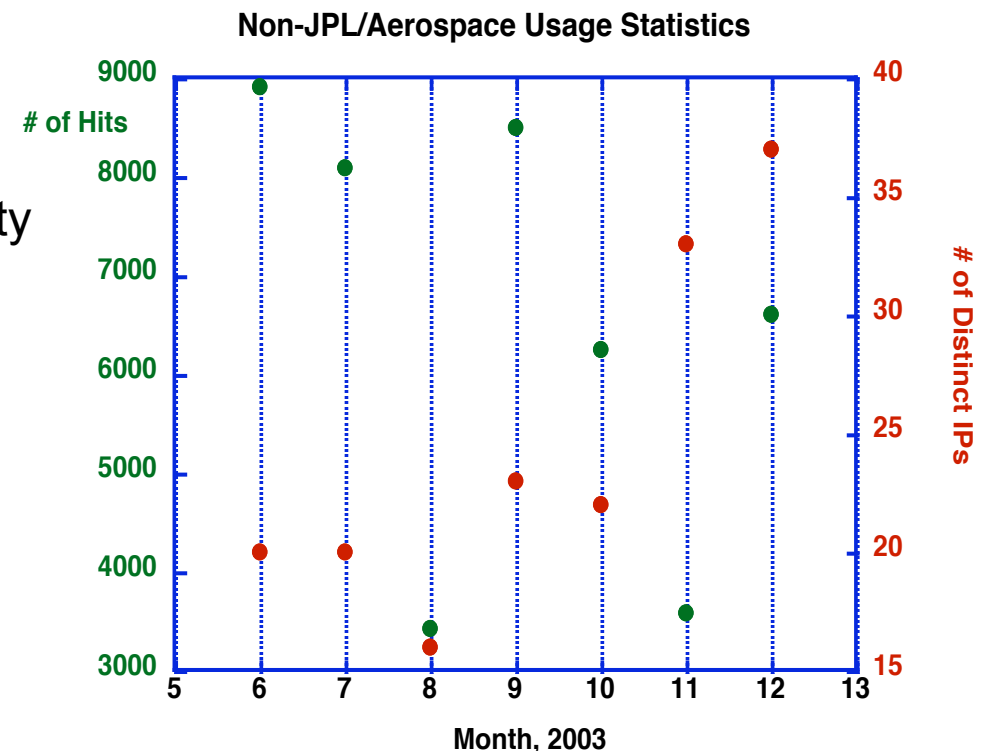
Positive Feedback



Feedback from 'beta' testers (mainly at 2SOPS) was uniformly positive

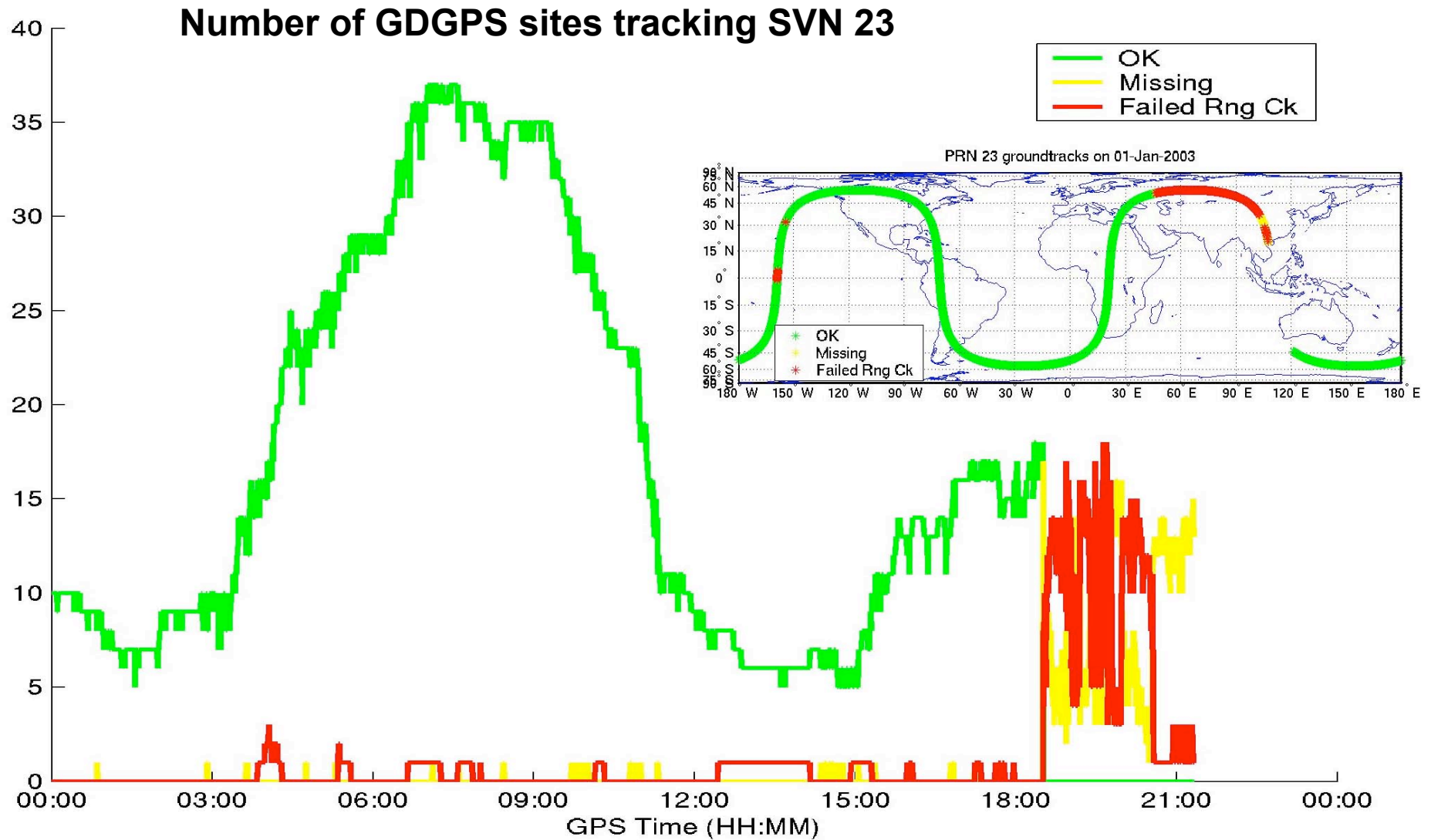
- It does not interfere with 2SOPS operational procedures. It is just *available*
- It provided operational assistance in diagnosing the constellation on several occasions
- Analysts use it from home extensively; enhances response time and efficiency
- Aerospace uses the monitor for development and analysis of novel integrity monitoring concepts

- The monitor has provided 100% availability to-date, with no known failures
- No false alarms
- All GPS anomalies monitored



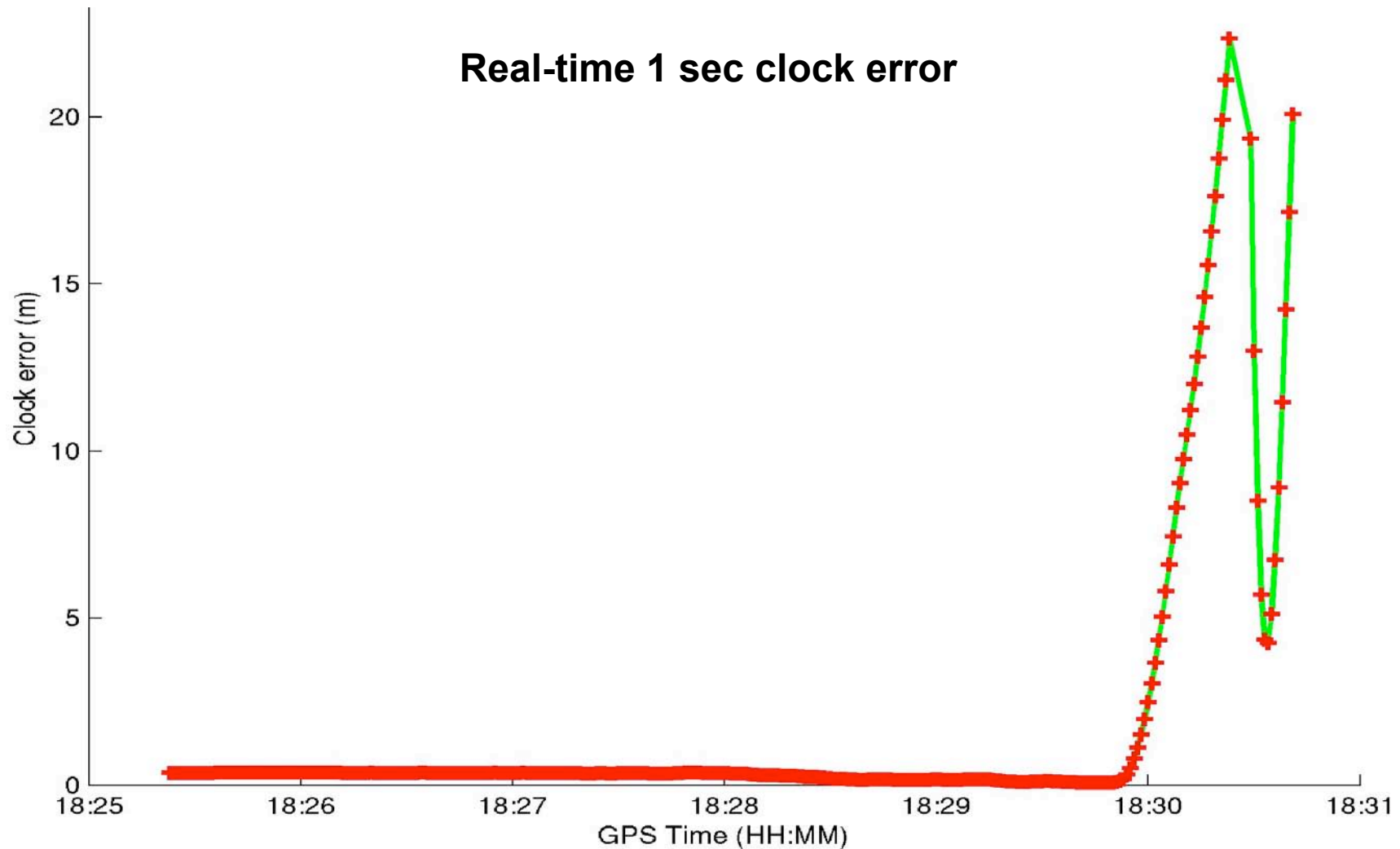


Example 1: SVN 23 on January 1 2004





Example 1: SVN 23 on January 1 2004 (cont)

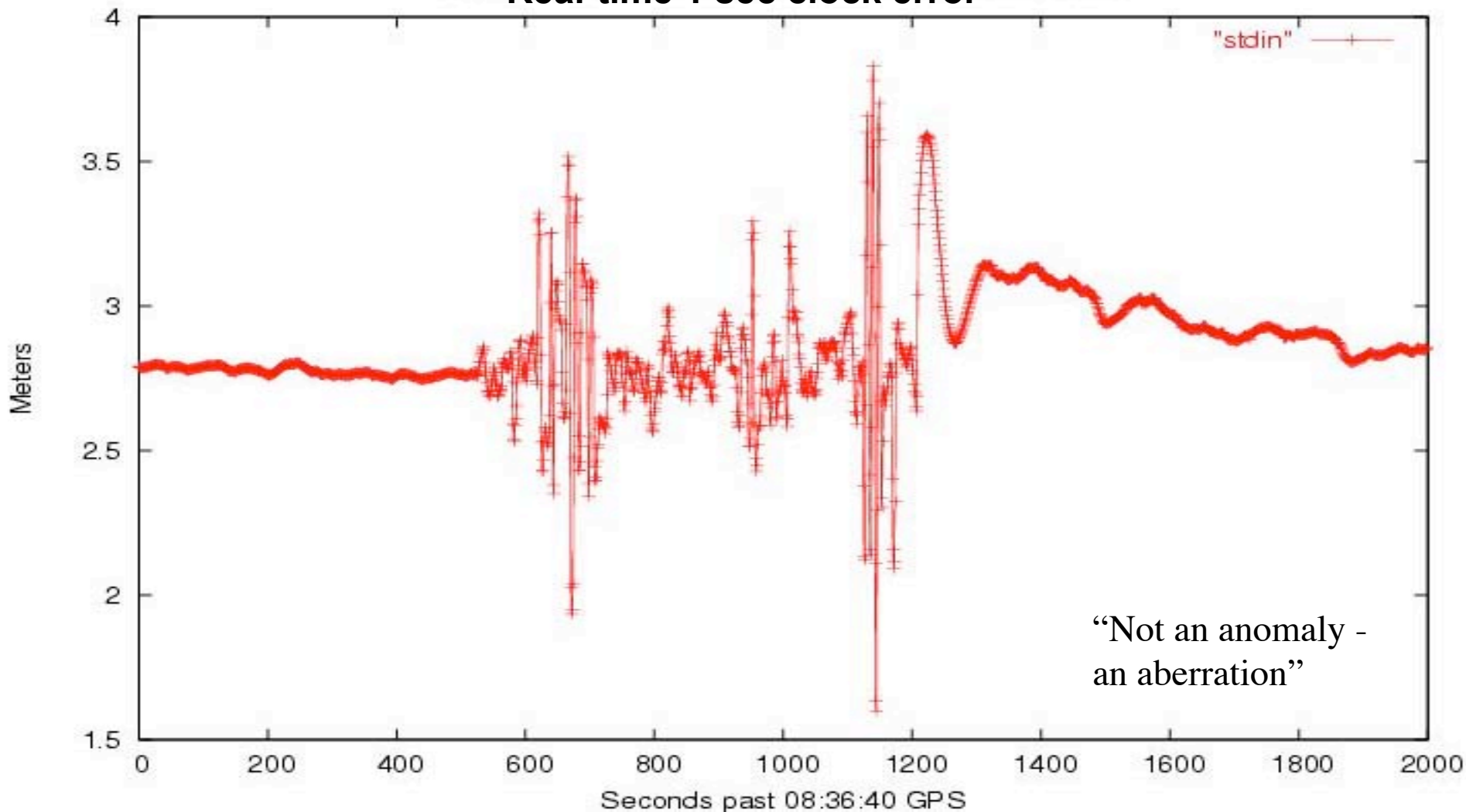




Example 2: SVN 46 on August 2003



Real-time 1 sec clock error





Future Developments



- Implement data authentication scheme
- 4 Second alarms
- Specially tuned performance monitoring process
- Refinement of web interface with user-feedback

- Perform failure mode and effect analysis (FMEA)
- Incorporate civil monitoring requirements developed under GDMS
 - New data types from ground reference network
 - New user interface
- Integrity data messages enabling automatic, forecasting, diagnosis, and response by responsible agencies
- Plan for evolving constellation (L2C, L5)
- On-going tuning and refinement based on user feedback
- Engage other agencies/monitoring system about sharing infrastructure, services
- Ever increasing reliability and robustness



Benefits



The prototype GPS performance monitor can provide an immediate measure of GPS integrity monitoring to the GPS operators

- Enable faster identification of integrity failures
- Enable quick diagnosis and response to integrity failures
- Enable prediction of integrity failures and plan for preventive measures
- Provide independent backup for the GPS ground segment

Improve situational assessment for civil/military GPS-based services

- High accuracy performance monitoring anywhere

Global augmentation system extends precise GPS operations to infrastructure-poor areas of the world



Vision



Convert the prototype GPS performance monitor into a fully operational system, jointly sponsored by several Government agencies

- Tune performance to user-specified requirements
- Upgrade communications and computing infrastructure to enhance reliability
- Provide on-going support and respond to the changing needs of constellation
- Share operational responsibilities (technology transfer)



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